ISSN 0040-6015, Thermal Engineering, 2014, Vol. 61, No. 11, pp. 790–796. © Pleiades Publishing, Inc., 2014.
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STEAM-TURBINE, GAS-TURBINE, AND COMBINED-CYCLE PLANTS AND THEIR AUXILIARY EQUIPMENT

Electrization of a Wet Steam Flow and Its Influence on Reliability and Efficiency of Turbines

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Abstract—Results of research into electrization of a moist steam flow are presented. The basic mechanisms of formation of electric charges and their influence on the reliability and the efficiency of a turbine are considered. The causes of the electrochemical corrosion of the blades are analyzed. The methods are developed to control thermal processes by artificial activation and deactivation of the charge density in the flow. A new method for diagnostics of coarse-dispersed moisture is proposed. Practical recommendations on how to increase the reliability and the output-input ratio of turbine units are presented and validated.

Keywords: steam turbine, electrization, reliability, efficiency, electrochemical corrosion, supercooling, diagnostics

DOI: 10.1134/S004060151411010X

The phenomenon of electrization was first described by Thales (approximately 600 BC) as a property of rubbed amber to attract light bodies; and only 2200 years later investigation of this phenomenon was continued by W. Gilbert, who showed in 1600 that the electrifying property is also intrinsic to other bodies. Then, in 1663, Otto von Guericke built a structure comprising a sulfur ball that, being rubbed against the palm when rotating, became electrified. He was also the first to observe electric repulsion in 1672. In the late 19th century, Ken showed that for two bodies to become electrified it suffices for them to touch each other and then separate. Thus, investigation of the electrization phenomenon was of an irregular character and advanced at an extremely slow pace.

Only at the beginning of the 20th century, rapid development of aviation and frequent fires and explosions caused by static electricity promoted research in this field [1]. The growth of industry required designing electric precipitators and facilitated development of the theory of electro-gas-dynamic systems and methods for computing them [2]. Numerous investigations showed that electrization and natural and artificial electrical fields can have a significant effect on natural phenomena and technological processes.

As for process gas, its electrization was first observed by lord W.G. Armstrong in 1861 at the exit from a steam-engine whistle. Now, it is obvious that the moist steam always becomes electrified when moving along various channels and it seems strange that in more than a hundred years of operating steam turbines this phenomenon not only was not studied but was not even discovered.

Nevertheless, electrization of the moist steam in turbines was first experimentally established and investigated by researchers under the leadership of the author of this paper only in the late 20th century. In 1992, the presence of electric charges was recorded in the steam flow of a 50-MW turbine at the TETs-2 combined heat and power plant in Kharkiv. The measured charge density downstream from the last stage appeared to be by one order higher than in a thunderstorm cloud and was approximately 10^{-3} C/m^3 at an electric field intensity of approximately 2×10^5 W/m. Further research at numerous thermal and combined electric power stations in Ukraine, Russia, and the United States proved this fact [3]. For example, during an experiment planned and conducted by Ukrainian (IPMash NAS of Ukraine) and American (Sonoma Research Company) experts on an 800-MW turbine at the Navajo Generating Station (Arizona, United States) in 1998 at which the author also actively participated, the charge density was measured and the distribution of the charges in the steam flow in the radial direction depending on the pH of feed water (see Fig. 1) was established. The measurements were carried out using an electrical probe installed on a movable traverse that could travel up and down the height of the stage. The charge density in the steam flow was varied within the range 10^{-7}–10^{-5} C/m^3.

Special research was carried out in the phase transition zone on a 750-kW ET-12 turbine (Moscow Power Engineering Institute, Russia) that recorded a charge density in that area of 10^{-10}–10^{-8} C/m^3 [4].

In this way, the dynamics of charge generation in the turbines' steam path was established. The density

of the charges can gradually increase approximately from 10^{-10} C/m^3 in the phase transition zone to 10^{-3} C/m^3 in the turbine exhaust.

The electrization of the wet steam flow occurs exclusively owing to electrization of the droplets contained in the steam. The water droplets may acquire electric charges when detaching from the surface of a metal or water or being split up in the flow owing to the electrolytic electrization mechanism.

The prevailing mechanism of generating a charge on a droplet is associated with the destruction of the electric double layer (Fig. 2) when the water film flows down from the blade surface. According to modern conceptions [5], an electric double layer occurs at the liquid–solid-body interface; this layer consists of ions of the same sign that are fixed to the solid body surface as a result of the action of electric adsorption forces, the Helmholtz layer, and a diffuse ion layer of the opposite sign, the Gouy layer. When moving along the blading section of a turbine, the steam flow entrains the water film formed on the surfaces of turbine guide and rotor blades; the electric double layer is destroyed in this case and the water droplets in the flow entrain the electric charge.

Consequently, generation of charges in a steam flow can be accounted for by the following factors:

(1) At the beginning of the phase transition zone, electrization of the steam flow occurs because of destruction of the electric double layer but, owing to a low moisture content, the charge density in the zone, as a rule, does not exceed 10^{-8} C/m^3; and

(2) In the turbine last stage and the exhaust areas, the electrization of the steam is caused by the destruction of the electric double layer and of large drops (balloelectric effect); the volume charge density at a high moisture content reaches the maximum value 10^{-4}–10^{-3} C/m^3 downstream from the last stage.

In the course of research, it was also established that [3]:

(1) The charge polarity of the primary droplets depends on the chemical compositions of the feed water and the rotor blade material; in the case of a standard feed water chemistry, the droplets acquire the positive charge upon detachment from stainless steel surfaces and the negative charge when breaking away from carbon steel and brass surfaces;

(2) Electrization can be controlled by altering the water-chemistry conditions or generating an electrical field in the charge generation area; and

(3) Electrization of a steam flow is one of the causes of the electric potential on the turbine rotor shaft.

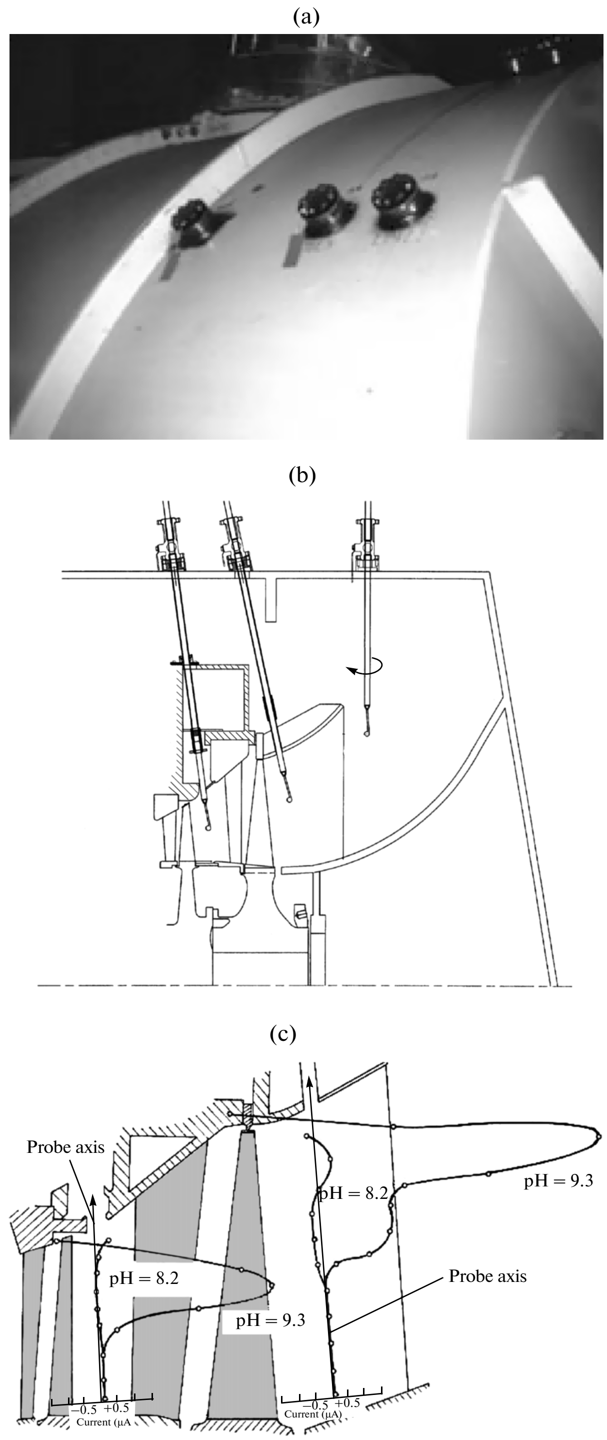

Fig. 1. Position of (a) special valves and (b) movable probes and (c) the results of measuring the charges in the steam path.

Effect of the Steam Electrization on the Reliability of the Turbine

Analysis of the existing concepts of the drop impingement erosion of metals [6] shows that, despite certain achievements in development of mathematical models and software that enable evaluation of probability of turbine blades' erosive wear, the nature of this phenomenon has not been clarified yet. Presently, the kinetics of the turbine blades' erosive damage is predicted and their lifetime is estimated on the basis of the

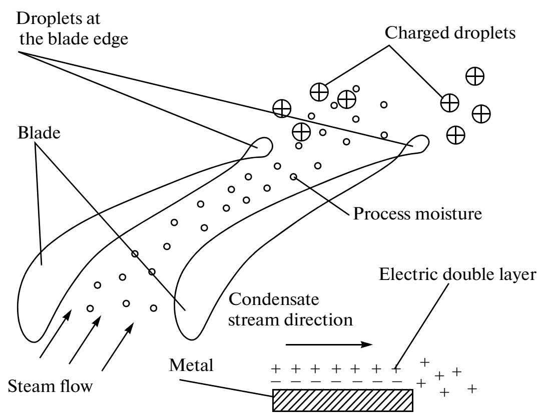

Fig. 2. Schematic of generation of the charges in a steam flow.

processes caused by elastic-plastic strains resulting from surface oscillations, the Rayleigh waves, and those resulting in fatigue failure. However, analysis and validation of the mechanism of development of acicular–saw-toothed surface geometry of the eroded blades have not been paid proper attention (see Fig. 3).

It is the author's opinion that such surface geometry cannot be explained by only mechanical impacts. Complex studies of the electrophysical processes that occur in the turbine last stages and in the exhaust area [3] show that the drop impingement erosion is a complex mechanical-electrochemical process of destruction of the material. The electrical phenomena that occur in a steam flow can cause:

(1) cathodic hydrogenation of the metal and, as a consequence, manifestation of hydrogen embrittlement;

(2) electroerosive or electro-spark damage; and

(3) destruction of the metal according to the anodic dissolution mechanism.

As a result of electrophysical processes that occur on the components of the turbine steam path, the water-steam flow acquires, as said above, the charge of one polarity while the structural components of the steam path, such as blades on the surfaces of which the flow becomes electrified, acquire the charge with the sign opposite to that of the steam flow. Consequently, between the sections of the turbine component surfaces that participate in electrization of the working medium and the sections of the surfaces on which the electrically charged working medium particles discharge, a direct electrical current flows, whose magnitude under otherwise equal conditions is determined to a great extent by the chemical composition of water and the gas-dynamic characteristics and the moisture content of the steam flow.

According to Faraday's law, when a direct electric current passes through an electrolyte, the electrolyte's chemical components are separated at the electrodes. In the case in question, the basic electrolyte component is water; therefore, upon its electrolytic dissociation, hydrogen H^+ (Fig. 4) and other positively charged ions will separate at the cathode while ions OH^- and other negatively charged ions will separate at the anode. Consequently, the cathodic sections of the surfaces of the steam path components will be subjected to hydrogenation, while the anodic sections will be subjected to the anodic etching. In addition to it, the same sections are subject to mechanical loads by impinging moisture droplets accompanied by pulse impacts of the electric current.

It is these phenomena that play the decisive role in altering the blade configuration and are responsible for the resulting acicular–saw-toothed surface geometry

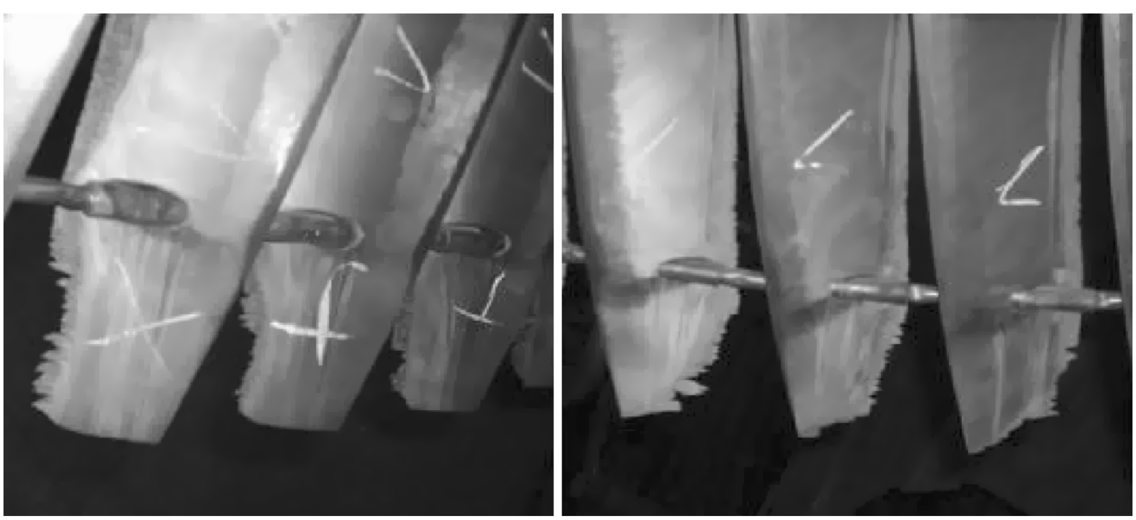

Fig. 3. Damaged fifth stage rotor blades of a 300-MW turbine LPC.

of the blades. Thus, one of the major factors in destroying the turbine blade material, coming after a direct mechanical impact, is the electrochemical impact.

Understanding these processes enables us to give recommendations how to prevent negative consequences of a structure's degradation, for example, by neutralizing the charges, heating the surface of the guide blades, selecting the materials that are less inclined to form hydrides upon hydrogenation, etc.

Effect of Steam Electrization on the Economical Efficiency of the Turbine

The study showed that the number of charged water particles/droplets in the phase transition zone that serve as the condensation nuclei, is obviously insufficient to affect the heat and mass transfer and the gas-dynamic processes to some extent.

At the same time, it was established that electrization of the steam affects the flow conditions most noticeably in the last stage, or, more precisely, at the exit from it. The point is that the charges that are produced in a moving flow form a volume charge whose electric power is directed towards the flow (see Fig. 4). If the volume charge density is very high, as is the case in the last stages, part of the flow's kinetic energy is spent on converting it into the energy of the electric field, reducing the velocity and increasing the pressure [3]. Moreover, as numerous experimental full-scale investigations show, the volume charge density and the electric field intensity are very nonuniform in both the axial and the radial directions and the electric fields and the currents resulting from the electrization are of an intermittent nature. All this causes additional pulsations in the flow and increases the pressure downstream from the last stage. For example, the voltage at the electrodes positioned downstream from the 50-MW turbine last stage measured approximately 30 kW and the electric force increased the pressure after the last stage by 200 Pa.

The method for increasing the turbine's efficiency developed by researchers of IPMash NAS of Ukraine, ensures rejection of the electric energy and neutralization of the charges, which eliminates the negative consequences of the natural electrization of the flow.

For this purpose, both active and passive neutralizers can be used. To neutralize a volume charge, it is necessary to increase the conductivity of the medium or add to the volume some charges equal in number and opposite in sign. In the first case, when the conductivity of the medium is increased, the volume charge is reduced owing to its drainage to the "ground." In the second case, in the compensation method, the charges of one sign present in the volume and the artificially added charges of the opposite sign are mutually neutralized. The method based on increasing the conductivity of the medium is simpler.

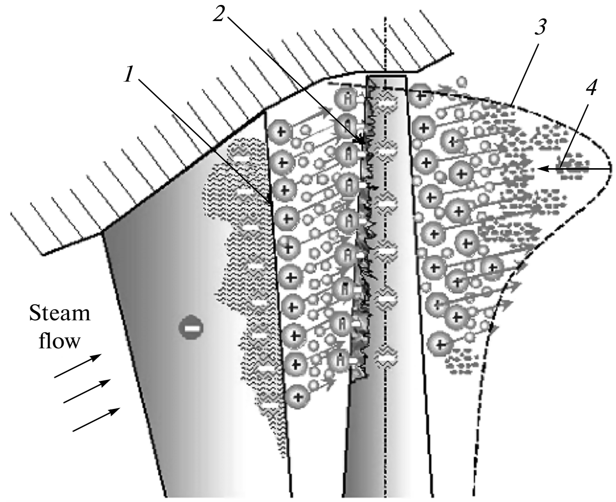

Fig. 4. Schematic of hydrogenation of the last stage rotor blade: (*1*) The trailing edge of the guide blade that acquires the negative potential, (*2*) the leading edge of the rotor blade periphery subject to cathodic hydrogenation, (*3*) the charge distribution across the blade height, and (*4*) the electric force.

The compensation method is more efficient but requires a highly precise addition of compensating charges to the volume; otherwise the compensation is not complete or overcompensation occurs and a charge of the opposite sign is formed in the volume.

Volume charge neutralizers of several designs were developed at the IPMash NAS of Ukraine and patented [7]; theses devices enable elimination of the volume charge's negative impact on the operation of the turbine. The overall view and the schematic of one of them are presented in Fig. 5. The neutralizers' designs were successfully tested on T-250/300-23.5 and T-37/50-8.9 turbines in Kharkiv.

Diagnostics of the Concentration of the Coarse-Dispersed Erosion-Threatening Moisture

Since the concentration of the coarse-dispersed moisture and the volume charge density are among the main sources of erosive and electrochemical destruction of the blades, the concentration of the erosion-threatening moisture has to be diagnosed. For this purpose, specialists of the IPMash NAS of Ukraine developed a diagnostic technique. The droplets formed upon volume condensation are very fine and always electrically neutral, while the coarse droplets formed upon detachment from the turbine blade surfaces bear an excess electric charge (see Fig. 2). This difference can be used to control the presence of coarse-dispersed moisture in the steam and changes in its concentration, which is extremely important for prediction of erosive damage of the turbine rotor blades.

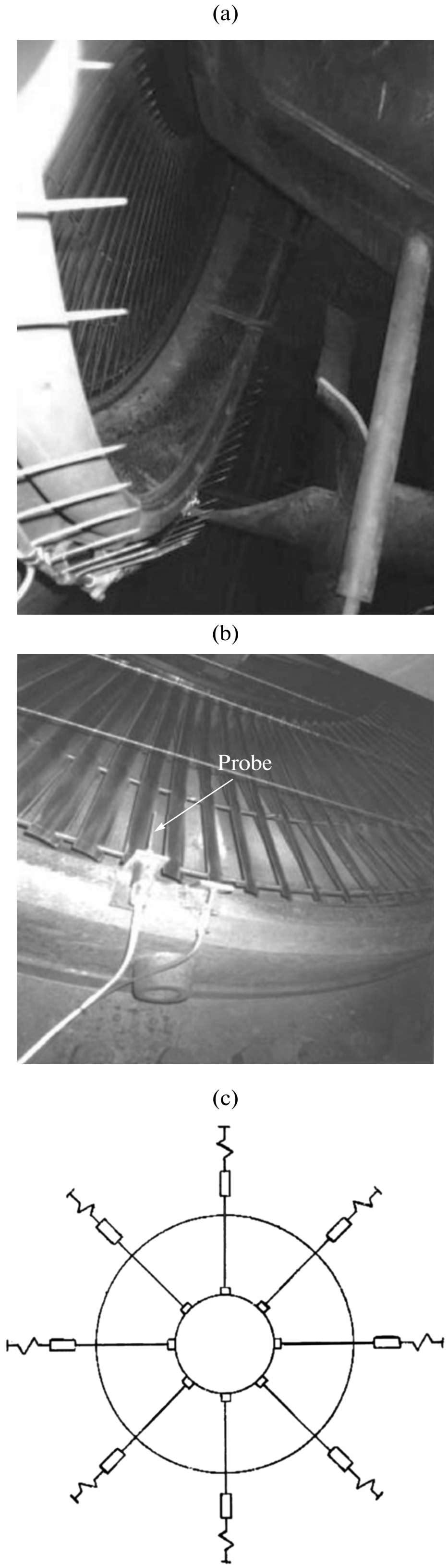

Fig. 5. (a, b) Overall view and (c) schematic of neutralizers at the exhaust duct. Neutralizers: (a) of pin-type and (b, c) of string type.

The volume charge density in a flow depends on the concentration of the coarse-dispersed moisture, the flow velocity, the chemical composition of the condensate, and the material of the blades [3]. When the turbine is in operation, the feed water chemistry and the flow velocity on the blade tip do not alter considerably and the blade material is constant; therefore, the volume charge density is determined predominantly by the coarse-dispersed moisture concentration. This circumstance allows determination of its distribution and variations in concentration by measuring the probe current in the steam flow. If a flow with volume charge q_v travels at velocity C across the surface with area $S_{\rm sur}$, the current flowing through this surface can be calculated by the formula [3]:

$$I_S = Cq_vS_{\rm sur}. \quad (1)$$

Measuring current I_S and knowing area $S_{\rm sur}$ of the probe surface and flow velocity C, we can find volume charge density q_v. The current and the flow velocity can be measured with required accuracy. To determine the volume charge density in the flow, one needs to know area $S_{\rm eff}$ of the probe's effective cross section since the electric field of a volume charge is distorted upon measuring the probe's short-circuit current in the steam, as a result of which $S_{\rm eff}$ increases, i.e., $S_{\rm eff} = S_{\rm sur}k_S$. Coefficient k_S of the probe's effective area depends on the flow velocity, the charge density, and the moisture content of the flow and can be found experimentally [3]. For a spherical probe 10 mm in diameter, $S_{\rm eff} \approx 17 \times 10^{-4}$ m^2 in the exhaust duct. The design of the probe is shown in Fig. 6.

Such a probe is notable for its ease of operation and high reliability and enables control of the coarse-dispersed moisture state at varying operating conditions of the turbine. When the electrical probe is installed in the steam path and downstream from the last stage via a special gateway device as shown in Fig. 1b, the probe current can be measured by the blade height; as said above, the current is proportional to the concentration of the coarse-dispersed moisture, which was proven by numerous experiments. The results of one of the experiments are presented in Fig. 7. The region of the maximum coarse-dispersed moisture concentration and the region of actual erosion damage of the blade tip almost coincide (100 mm apart from the blade tip).

Since, in practice, the erosive wear is observed in most cases in the vicinity of the blade tip, to enable continuous control, installation of a stationary electrical probe in this region (see Fig. 5b) is recommended to identify the most dangerous turbine's operating conditions.

Control of the Thermal Processes by Artificial Ionization of the Steam Flow

Understanding of electrophysical phenomena that occur in a turbine enabled development of a method for control of the thermal processes, which increases

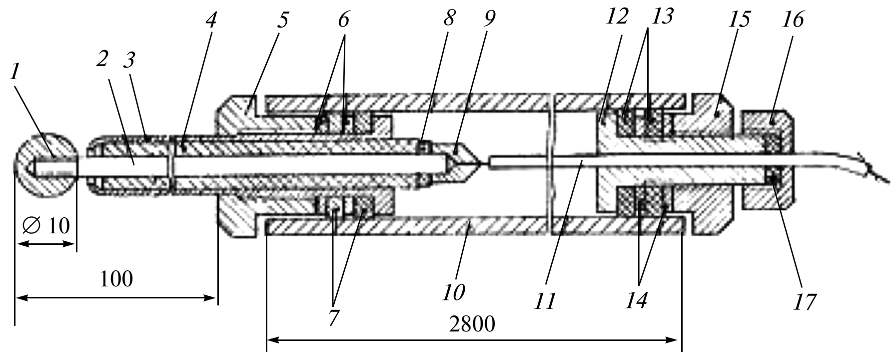

Fig. 6. Electrical probe: (*1*) receiving component (a sphere), (*2*) electrode, (*3*) casing, (*4*) insulator, (*5*, *8*, *9*, *15*, *16*) screw-nuts, (*6*, *14*) washers, (*7*, *13*, *17*) rubber gaskets, (*10*) rod, (*11*) cable, and (*12*) bushing.

the operational efficiency and the reliability through artificial activation of the charge density by supplying the electric energy to the steam flow in the phase transition zone where, as said above, there is a deficiency of condensation nuclei.

It should be noted that the prominent scientist A. Stodola detected a difference between the condensation under real conditions and that in equilibrium state—the former is delayed. As a result, the steam temperature drops below the saturation temperature, i.e., the steam becomes supercooled. In this case, its specific volume and, consequently, expansion work are reduced, which is one of the causes of decreased output power of modern turbines by 0.4–0.7%.

As the steam expands, the supercooling reaches the critical (limit) value, after which a spontaneous condensation occurs, which is accompanied by pressure jumps and changes in other thermodynamic characteristics of the steam. Such condensation unsteadiness initiates oscillations in the steam flow with a frequency of 500–2000 Hz, which promotes further oscillations, results in a 40–50% increase in the voltage, intensifies the corrosion-fatigue processes, and can lead to rotor blade failure. It is the opinion of many experts [8] that the damage of the stages that operate in such an unsteady environment accounts for 20–25% of the total number of accidents in turbines.

The attempts to control the volume condensation process have not found any industrial applications so far. For example, dosed supply of chemical additives to the feed water to produce condensation nuclei appeared to be expensive due to the necessity of continuous application of treating chemicals. Moreover, the reagent decomposition products may have an adverse effect on the reliability of the turbine.

The technique for generation of condensation nuclei by artificial ionization of the steam flow upstream from the phase transition zone first proposed in [9] appeared to be the most effective in terms of its practical application. Theoretical and experimental studies, including the full-scale ones, showed that the concentration of artificial, generated by ionization, nuclei at which no condensation jump occurs and the process is maximally close to an equilibrium process is $J_g \approx 1.4 \times 10^{15}$ kg^{-1}. In this case, the energy consumed to ionize the steam makes up 0.03–0.15% of the energy released upon the steam condensation. As an ionization source, a barrier discharge generator should be used that ensures a quasi-neutral steam that does not cause any electrocorrosion in the steam path [3].

Analysis of potential applications of the steam ionization in the steam path of the low-pressure cylinder (LPC), for example, in the K-300-23.5 turbine, showed that its capacity gain under the rated operating conditions will be 1500–2000 kW with an energy consumed to ionize the steam of 5 kW at most.

The greatest effect of implementing the proposed technology can be achieved if the positioning of the ionization device is taken into consideration as early as in the design or retrofitting phase as it depends on the pro-

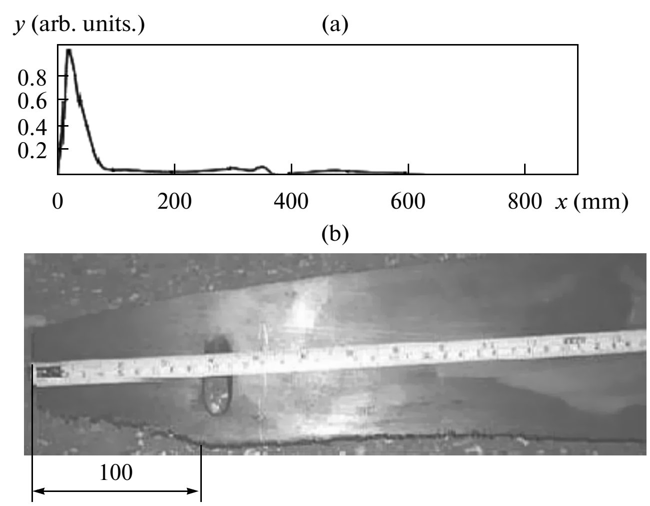

Fig. 7. Impact of the coarse-dispersed moisture on the last stage blade of a 300-MW turbine LPC: (a) the distribution of volume charge density *y* across blade height *x* and (b) an eroded rotor blade after 87 000-hour operation.

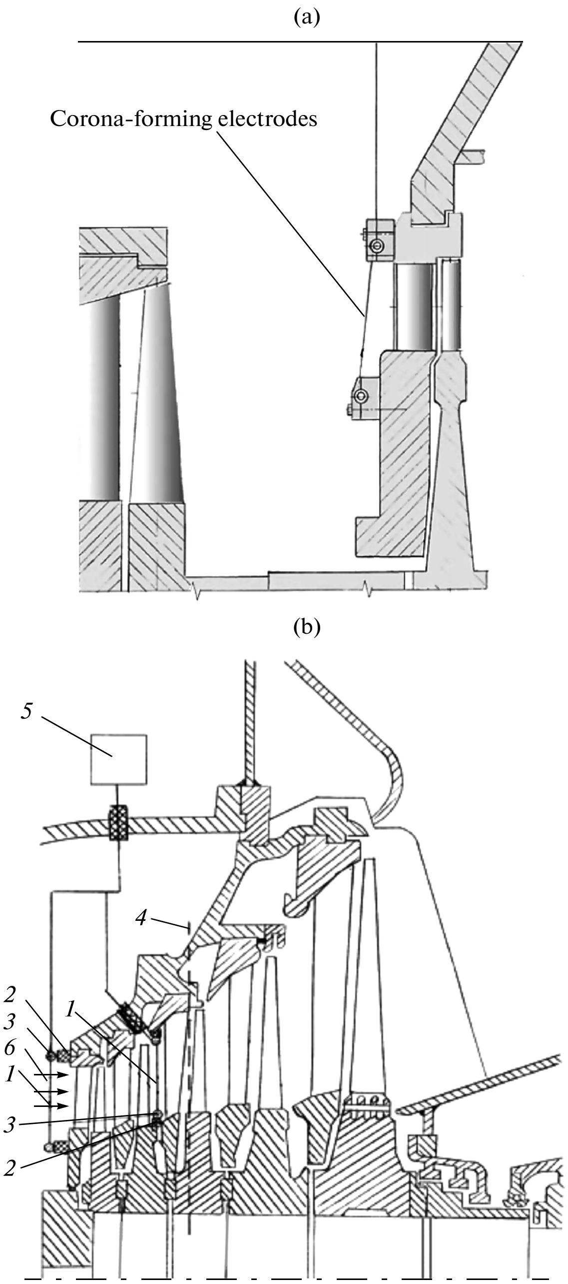

Fig. 8. Positioning of the corona-forming electrodes for ionization of the steam flow in the steam path: (a) upstream from the LPC first stage and (b) directly in the LPC steam path: (*1*) corona-forming electrodes, (*2*) insulator, (*3*) header, (*4*) condensation initiation zone, (*5*) high-voltage source, and (*6*) steam flow.

cess's thermo-gas-dynamic parameters that determine the initial phase transition zone in the steam path.

In Fig. 8, the possible variants of the steam ionization in the steam turbine LPC are shown. In addition, a possibility of placing the ionization device outside the steam path is considered, which will considerably simplify the practical implementation of the proposed technology.

All the above-mentioned studies were conducted on the test benches of the IPMash NAS of Ukraine and at Ukrainian, Russian, and US thermoelectric power stations and combined heat and power plants. The results of these studies enabled identification and validation of the major factors that cause the electrochemical corrosion of the turbine blades. As a result, a new method for diagnostics of changes in the coarse-dispersed moisture concentration was developed and practical recommendations were made for increasing the reliability and the output–input ratio (by 0.5–0.7%) of the power-generating plants by controlling the thermal processes through activation and deactivation of electric charges in a steam flow.

ACKNOWLEDGMENTS

I am grateful to V.P. Sklyarov, Dr. Sci. (Eng.) and N.V. Surd, Cand. Sci. (Eng.), for a considerable scientific and practical contribution to the study of electrophysical phenomena in steam turbines.

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Translated by O. Lotova